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Structural Interpretation and Time-Depth Conversion Based on 2D Seismic Data of Indus Offshore Area, Pakistan

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Keywords: strata correlation, structural interpretation, time-depth, conversion, Indus offshore area

ABSTRACT

Indus offshore basin of Pakistan is a prolific region for hydrocarbon resource exploration, however along with the availability of limited geological and geophysical data, an attempt has been carried out in this area. Data from a seismic strike line 9033-86 which contains shot points 1481 to 3361 have been considered comprehensively with remarkable and incredible calibration. Seismic interpretation techniques were used to understand five important reflectors the Upper Cretaceous, Eocene, Lower and Upper Oligocene, and Intra Miocene successions. Structurally, the area comprises of normal faults i.e., horst and graben structures on the seismic profiles. Three normal faults have been recognized in the region, which reflects the extensional regime and associated structural styles. Through analysis of vertical and lateral velocity variations of various geological layers, interval velocity and average velocity graphs have been prepared from the concerned velocity functions. According to the time-depth conversion model, depth contour maps outline the Eocene units with anticline and syncline. The trend of these reflectors shows that these are more or less parallel to each other while dipping towards the northwest which may provide a suitable structure for the accumulation of hydrocarbons. Therefore, an integrated study of accurate seismic interpretation, structural analysis and time-depth conversion provided a promising site for future hydrocarbon exploration.

INTRODUCTION

For the assessment of hydrocarbons, geological as well as geophysical techniques are applied that provide the evidence of the extension of surface structures into the subsurface and construct a suitable correlation (Moghal 2007; Riaz et al., 2018, 2019; Abid et al., 2019 a, b; Dar et al., 2021a). Hydrocarbon exploration requires a detailed representation of subsurface geological perspectives and structures, which provides an understanding of a basin's framework and structural styles. The study area (23° 15’ to 24° 30’ N; 66° 30’ to 67° 30’ E) is the part of Indus offshore Basin of Pakistan. The Offshore Indus Basin is about 120 kilometres south of Karachi, Pakistan, in the eastern Arabian Sea (Figure 1). Tectonically, it is located on the Indian Plate's northwestern border and has a geological history of around 200 million years (Gaedicke et al., 2002; Chatterjee et al., 2013). Several researchers have investigated the area and explored the hydrocarbon bearing area of offshore Indus that contributes to the oil and gas requirements of the country. The gas-prone region of the Offshore Indus Basin lies on the edge of the Indian continental crust and adjacent oceanic crust Wandrey et al. (2004). Since the 70s more than 15 wells (four in the Makran and eleven in the offshore Indus) have been drilled to date. Out of them, only two wells, Pak G2–1 and Anne-1 in the deep water.

Indus Offshore contains clastic and carbonate rocks, when the carbonate depositional cycles function over a scale of a few meters, seismic interpretation becomes a challenging task. This problem leads us to a poorly determined stratigraphic configuration (e.g., progradation) on a seismic scale. In this circumstance, the seismic response shows a general aggradational area that can be erroneously interpret as transgressive systems tract or as a high stand. To overcome this issue, an attempt has been made in this current research which can be valuable for future hydrocarbon exploration in this area.

GEOLOGICAL SETTING

Geologically, the Offshore Indus Basin of Pakistan is considered as a part of Gondwanaland, which later on separated as a small plate. The basin can be divided into three important zones, which are Makran Offshore, Murray Ridge, and Indus Delta and Indus Offshore Basin Kolla and Coumes (1987) (Figure 1). In the northwest which is a major plate boundary between the Indian and Arabian Plate, the basin is bounded by the Murray Ridge-Owen Fracture Edwards et al. (2000) (Figure 1). Indian, Eurasian and Arabian plates make a triple intersection in Pakistan offshore. The Carlsberg Ridge, which extends northwest and finishes into the Owen Fracture Zone, is the dispersed focus along which the new oceanic crust of the Indian Ocean is forming Jacob and Quittmeyer (1979).

propagated 150 km southward to the current location. The Fan shaped delta ranges over an area of about 30,000 km2. The rifting of the Indian plate from Gondwanaland, the opening of the Indian Ocean, and Himalayan tectonics are all intertwined in the geological history of the submerged Indus Basin. The Indus Offshore basin covers 20,000 km2 of the continental shelf. The Horst-Graben complex is located on the shelf. Shelf width is 100-150 km of the Gulf of Kutch-Indus Offshore Delta and widens to 350 km off the Bombay farther south, and the Shelf Break occurs at an

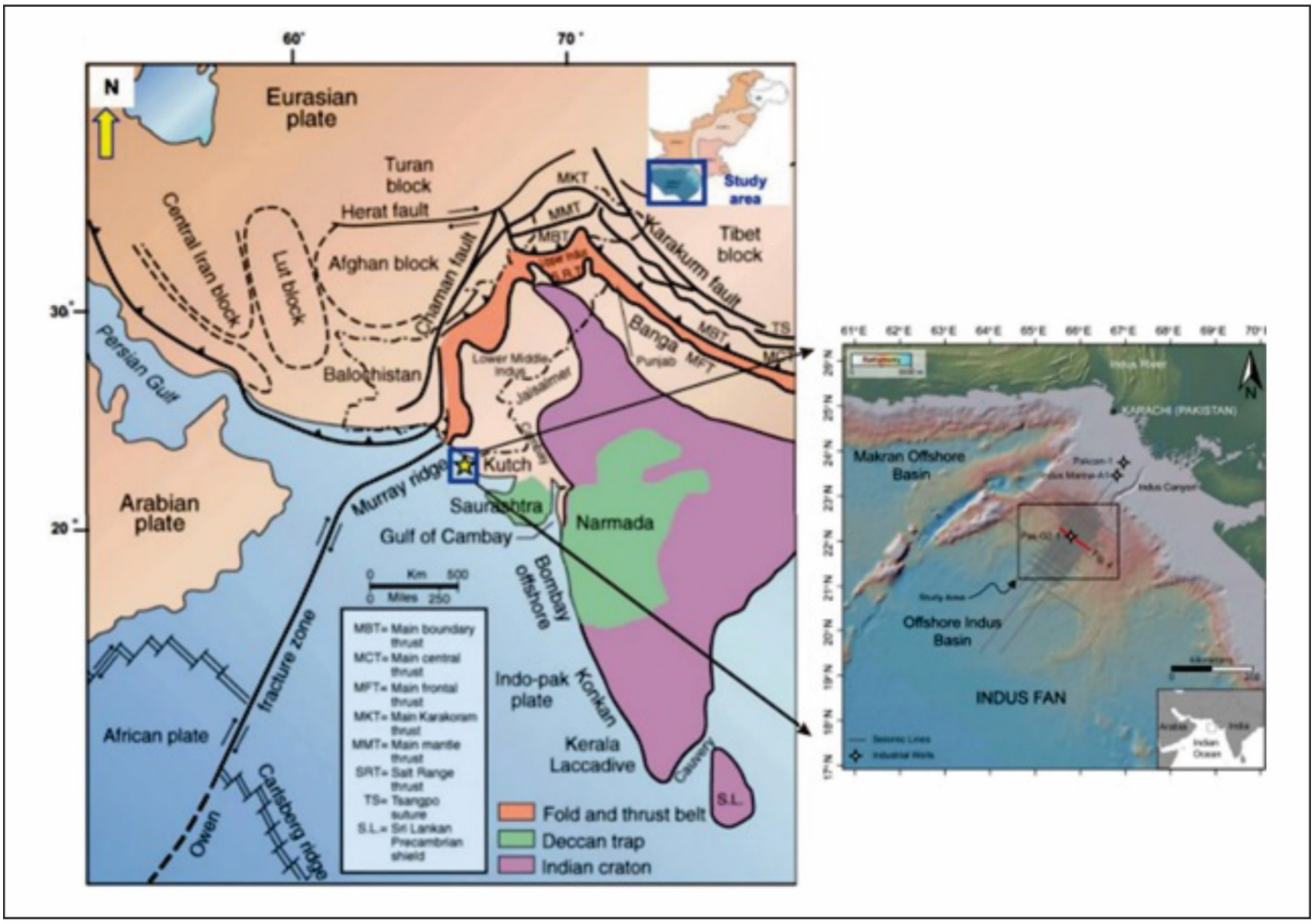

Figure 1 Map showing the geologic setting of study area (modified after Quadri and Quadri 1998; Khan et al., 2016) and location of wells shown via satellite image

Pakistan's eastern coast between Cap Monz and Run of Kutch contains the Indus Delta region, tectonically a passive coast. The most considerable geomorphic features of the Indus Offshore Basin and the Indus Delta are found along this coast. Coastal morphology depicts the features of tidal creeks, mud banks, and small islands in tidal channels, swamps and lagoons. The Indus Delta, which is built by the deposition of sediments of the Indus River is one of the largest deltas in the world. The geological history of this delta started during Early Miocene when it developed in the Bugti area. The delta has average depth of about 100 m along the Pakistan India Border. Since the Miocene, the Indus River has been delivering sediments through the submerged canyon and leveed channel systems Kolla and Coumes (1987).

At the lower end of the continental slope, the continuous depositions of the sediments have given rise to a large submarine fan, known as Indus submarine Fan. This is regarded as the second largest Fan around the globe, extending in the south from the Pakistan passive margin to Carlsberg Ridge, in the east and west bounded by Chagos-

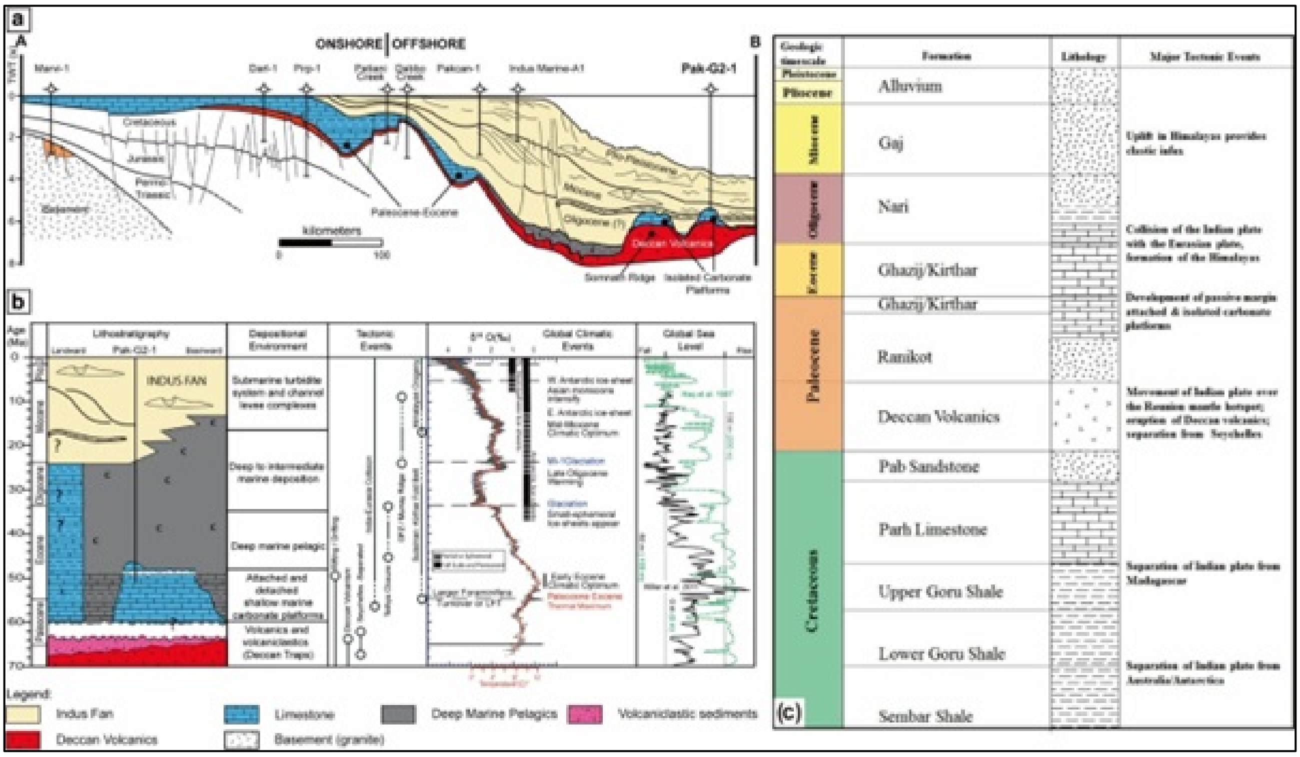

Figure 2 (a) The Regional cross-section of the Indus Offshore Basin and adjacent onshore basin (modified after Carmichael et al., 2009). (b) Regional stratigraphic relationship between studied carbonate platform and other stratigraphic sequences in the Indus Off

Lacadive Ridges and wen Murray Ridge Zone respectively. Sediment thickness inside the fan ranges up to 7 km. The transportation of the terrigenous material is triggered mainly by turbidity and tractive bottom currents (Dar et al., 2021b). The stratigraphic chart of the Indus offshore of Pakistan is given in figure 2.

PETROLEUM SYSTEM

The profound deep-water Indus offshore Basin is a frontier region for hydrocarbon exploration. Out of fifteen wells, only (Pak G2–1 and Anne-1) have been drilled in the deep water. Khan et al. (2016) reported that Miocene sand and Eocene carbonates are the main reservoirs in the Indus offshore. The deltaic type shale of Oligocene, Miocene and Pliocene has total organic content (TOC) ranging from 0.6 to >3.7 % are the source rock of the area (Wandrey et al., 2004). The organic matter comprises type II and type III kerogens while maturation arises throughout the late Miocene and Pliocene with the generation of hydrocarbon persistent today (Wandrey et al., 2004; Khan et al., 2016). Moreover, the area comprises four main types of traps; rollover trend, drape play, start traps and shale diapers Carmichael et al. (2009). Mudstone work as a seal however multifaceted sequence of erosional channels in the upper slope may interrupt and break some horizons.

METHODOLOGY AND DATA ANALYSIS

This research is an effort to explore the subsurface geology of Indus Offshore. First of all, base map was prepared that shows the location of the well and seismic line 9033-86 (Figure 3).

Moreover, 2-D seismic reflection data of the line and shot points 1481 to 3361 have been used to identify the prominent stratigraphic horizons, comprehend the tectonics and structural trends, and delineate the subsurface target horizons in the study area. Various parameters of the seismic lines (i.e., root mean square velocity, interval velocity, average velocity and mean average velocity graphs) have been applied to investigate the lateral and vertical geologic variation in the area. Besides, the data is used to know the procedures involved in the acquisition and understanding of the processing phenomenon in order to assess the quality of data, velocity analysis as a parameter, preparation of time and depth sections, structural interpretation of the subsurface using seismic data, preparation of the depth, time and velocity contour maps on the basis of seismic data, stratigraphic setting of the area. Moreover, variograms are prepared to show the variation between time and depth at a particular level. The acquisition and processing parameters are given in the Table 1.

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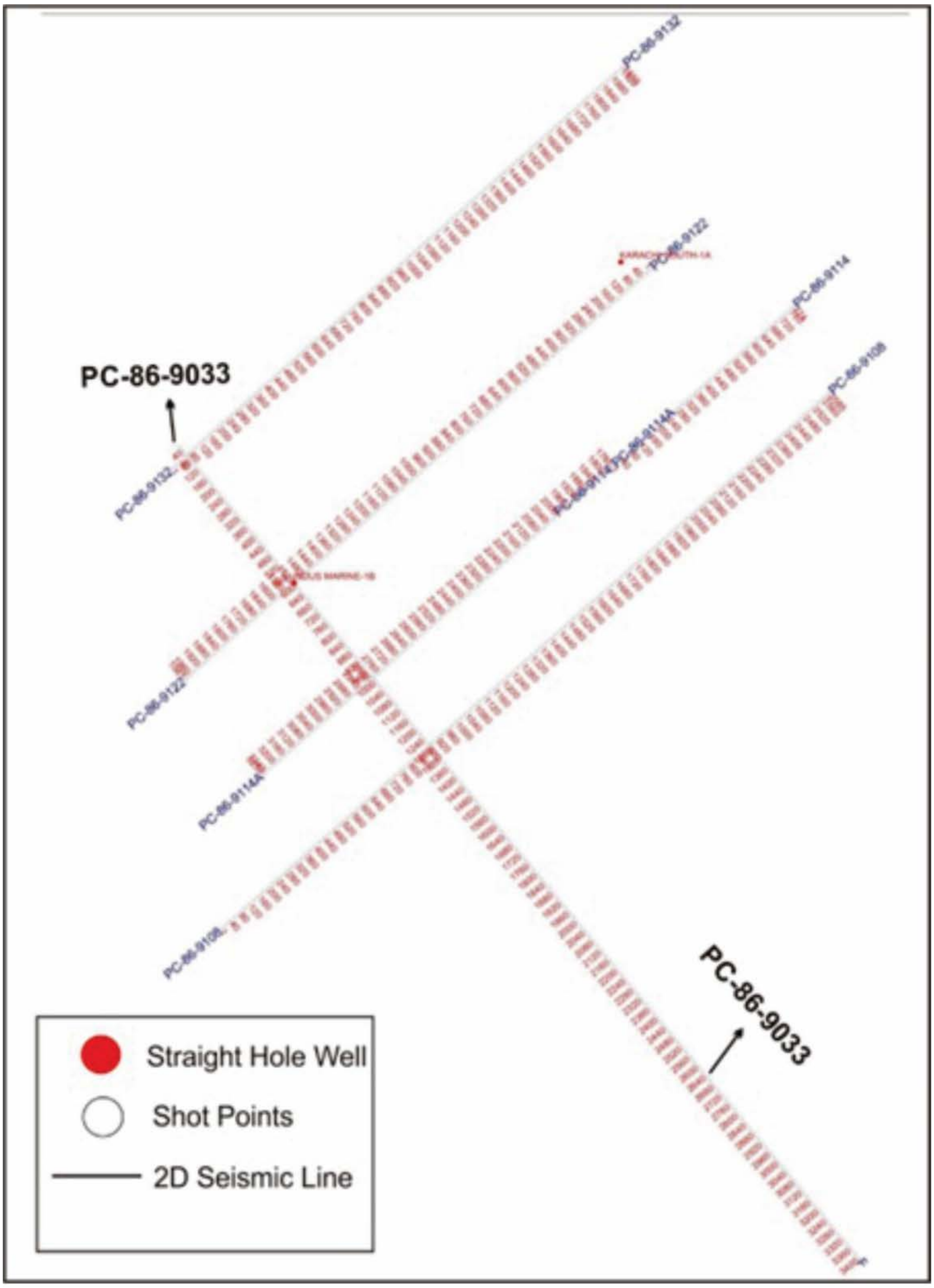

Figure 3 Base map of showing orientation of the 2D seismic line

Solving the Velocity Time Pairs

To find the interval and average velocity functions, the functions of root mean square (RMS) velocity on a given seismic section are prepared by using the software K-tron VAS (Velocity Analysis System) (Ashraf et al., 2016; Abbas et al., 2019), as shown in Figures 4, 5 and 6a. The steps involved in the process including 1) by keeping the specific format, the velocity time pairs are entered in notepad; 2) The RMS velocities are changed into interval velocities, and after that from interval to average velocities; 3) Finally the velocity time (VT) pairs are included (Ashraf et al., 2016; Anees et al., 2017).

Table 1: The acquisition and processing parameters

Acquisition and processing parameters	Source: dynamite	
	Average depth shot	1m
	Charge size	3kg
	Source type	bolt par air gun
	Shot point interval	25m
	Receiver	LITTON WMI-0045
	Receiver/group	
	No. of groups	20 over 25 meters
	Group interval	20
	Recorder type	25m
	Tape format	DFS V
	Processed by	SEG B
	sample rate	Geo-x
	CDP interval	2ms
	Average fold	25m
	Wave-speed model	60
		1d

Root mean square velocity graph

The amount of weighing is determined by the value of interval velocities since the RMS velocity is a weighted average, which is utilized in the weighing process. Weighing is done by squaring the interval velocity values (Robinson and Coruh, 1988). RMS velocity equation is given as:

$$v_{rms}^2 = \frac{\sum_{i=1}^{n} v_i^2 t_i}{\sum_{i=1}^{n} t_i}$$

By using the K-tron VAS (Velocity Analysis System) the RMS velocity functions given on a seismic section are processed to compute interval and average velocity functions using Dix equation (1955). Equation proposed by Dix is given by:

Interval velocity graph

The average propagation velocity through a depth or time interval is the interval velocity, and it equals the width of the depth interval divided by vertical time through

$$V_{\text{int},n}^2 = \frac{V_{rms,n}^2 T_n - V_{rms,n-1} T_{n-1}}{T_n - T_{n-1}}$$

the interval. Depth intervals are characterized by Δz, i= 1, 2, 3…N (Gadallah and Fisher, 2005).

V=Δz/Δt

Average velocity graph

The Average Velocity is solely the depth 'z' of a reflecting surface under a datum divided by the detected one-way reflection one-way time (t) from the datum to the surface, described as:

Vave = z / t

Average velocity was calculated the same way as the interval velocity by using K- tron (software), as shown in Figure 6a. By using VAS file format, the average velocity was calculated and then generated for each velocity function.

Mean average velocity graph

The mean of all the average velocities at any specific time implies as the mean average velocity. It signifies the overall increasing trend of the average velocity with respect to time. The mean average depth of the seismic section is calculated and evaluated by using this velocity. The mean average velocity graph displays the disparity of velocity with time, which is the mean of all CDP's at the same time. It demonstrates the overall trend of velocity or mean of all velocities with respect to time i.e., as time increases, velocity increases, and with the increase of depth, velocity increases due to the compaction of rocks, as shown in Figure 6b.

RESULTS AND DISCUSSIONS

Interpreted Seismic Section

In a conceptual framework, the seismic stratigraphic interpretation of carbonate rocks is usually different from clastic rocks interpretation (Khan et al.,

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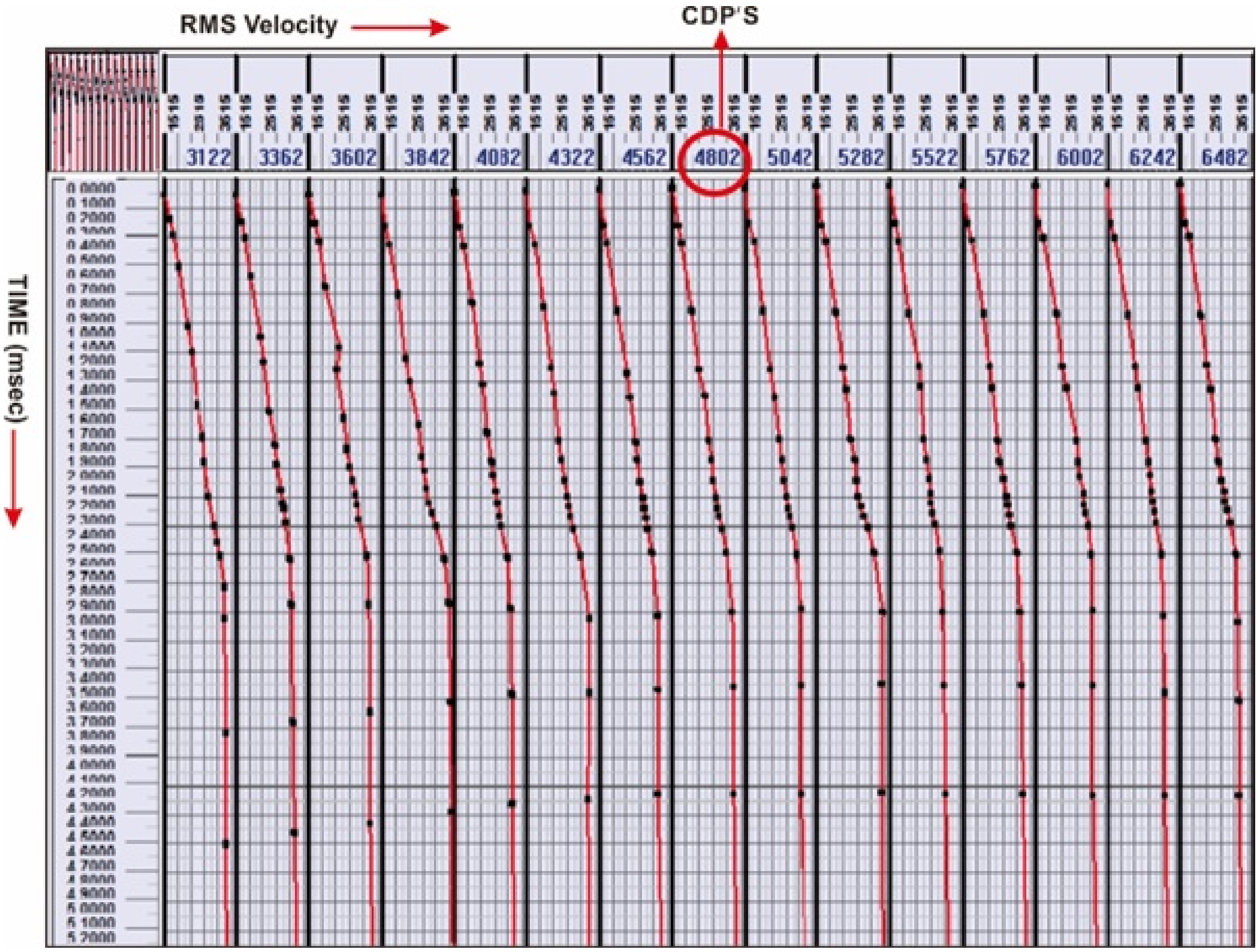

Figure 4 Root mean square velocity of the line 9033-86

2016). Carbonates and siliciclastic sedimentary systems are principally different in two ways: carbonates are autochthonous in origin and susceptible to early diagenesis. In particular, carbonate lowstand system tracts are not well advanced, because during sea-level fall, carbonate sediments become lithified whereas siliciclastic deposits are reworked downslope (Farzadi 2006). The sequence model of carbonate lowstand system tracts is only a minor component whereas comprises of a higher proportion of lithostatic grains (Khan et al., 2016).

The seismic line 9033-86 used in our study display some structures of the strata deposited in the Indus Marine A1 well (Figure 7a). The comprehensive detail of the entire strata on each seismic line is hardly possible. The northwest-southeast oriented (Figure 3) seismic section of lines 9033-86 is loaded by using X-work, and horizons and faults are marked. Horizons are assigned a colour, so that all the horizons may be differentiated from each other. All faults are marked in black colour. A sum of five reflectors and several faults have been shown on the interpreted seismic section of lines 9033-86 (Figure 7b). The northwest portion of the section shows a chaotic configuration of reflectors. A feature similar to velocity sag is noticeable in the section, and it has a definite impact throughout the section, thus causing the downward fluctuating of horizons (Figure 7b). This pull-down shows the existence of a buried canyon. The upper cretaceous, upper Oligocene and intra Miocene highly depict distortion as compared to the Eocene and lower Oligocene (Figure 7b).

Seismic Time Section

The seismic time section display the cross-section of the earth that is composed of different seismic shots. Moreover, vertical and horizontal scales show us the arrival time and shots points respectively. The time section map of line 9033-86 depicts the variation of TWT from northwest to southeast (Figure 7c). In the northwest section of the map TWT range from 6000sec to 2000sec whereas in the southwest section of the map display 4800sec to 2000sec. The higher values of TWT in NW depict the downward

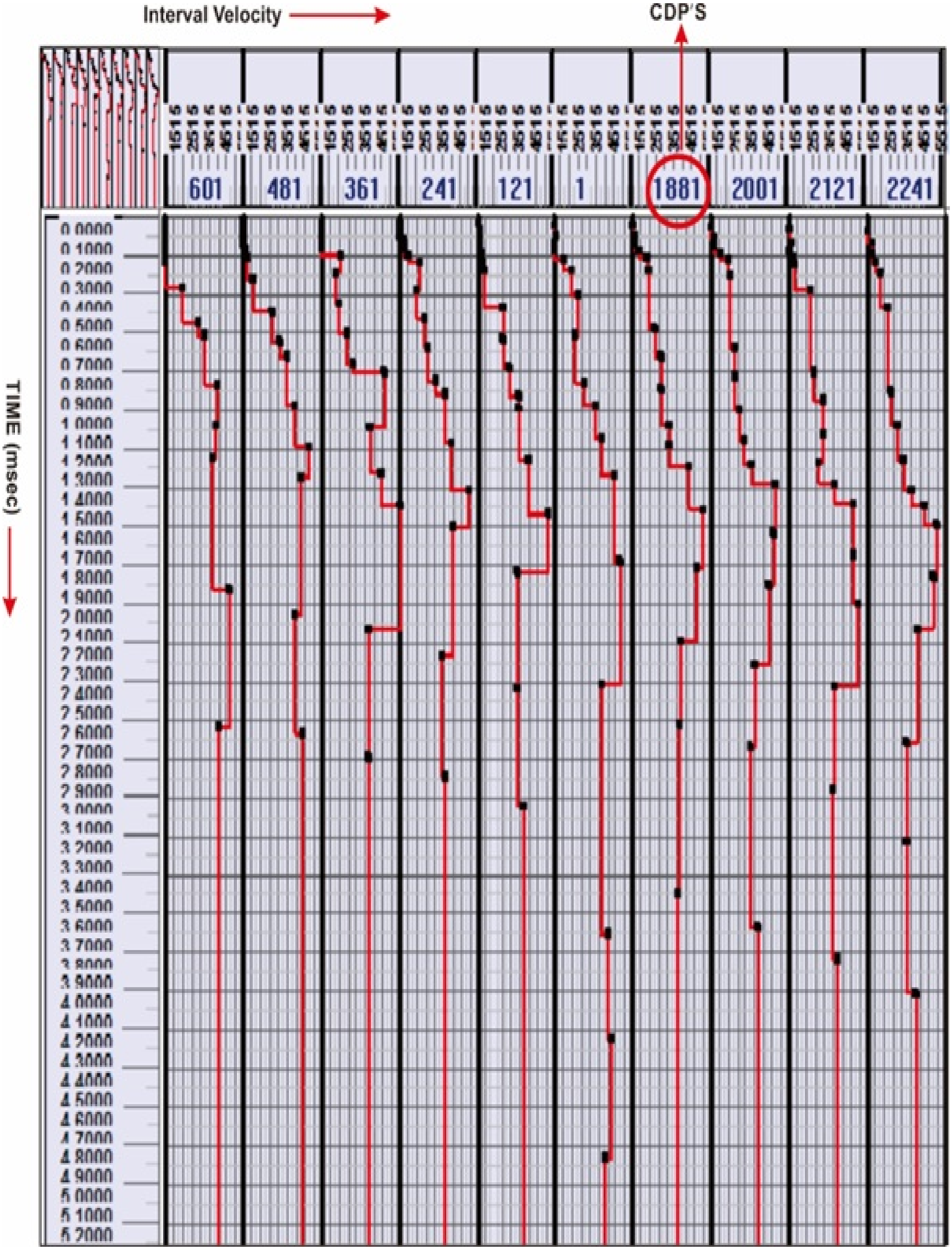

Figure 5 Interval Velocity of the line 9033-86

movement due to the canyon structure. The higher value of TWT also shows the possibility of tectonic forces which might be higher in NW as compared to SE and they built the normal faults i.e., horst and graben structures.

Seismic Depth Section

The vertical unit of the seismic section represents the two-way time that may not be a deliberate clear image of the sub-surface structure, so we change the time section into the depth section. The depth section maps portrayed the thickness discrepancy of prospective hydrocarbon strata. The depth map depicts the variation in depth from NW to SE (Figure 7d). The Northwest portion show a higher depth as compared to the southeast, which also clarifies the downward movement of the area either due to canyon structure or the influence of higher compressional force in this area.

Time and depth contour map of Eocene

The time and depth contour maps of the top of Eocene were built by using several lines including PC/9033-86, 9114-86, 9122-86 and 9032-86 (Figure 8). The pattern of both the contour maps confirms the sub-surface shape of the structure. The time contour map of Eocene shows 2D with time, while the Time-Surface contour map provides a 3D visualization of the sub-surface structure during Eocene time (Figure 8a-b). The colour variation from light blue to red in the time surface map of Eocene shows the time variation from minimum to maximum. Where there is a minimum time there is an anticline, whereas maximum time shows syncline.

The depth and surface contour map of Eocene show the variation in depth. The center part displays higher depth while the surrounding areas depict lower depth. The variations in depth clarify the syncline in the center while anticline in the surrounding area of the studied section (Figure 8c-d).

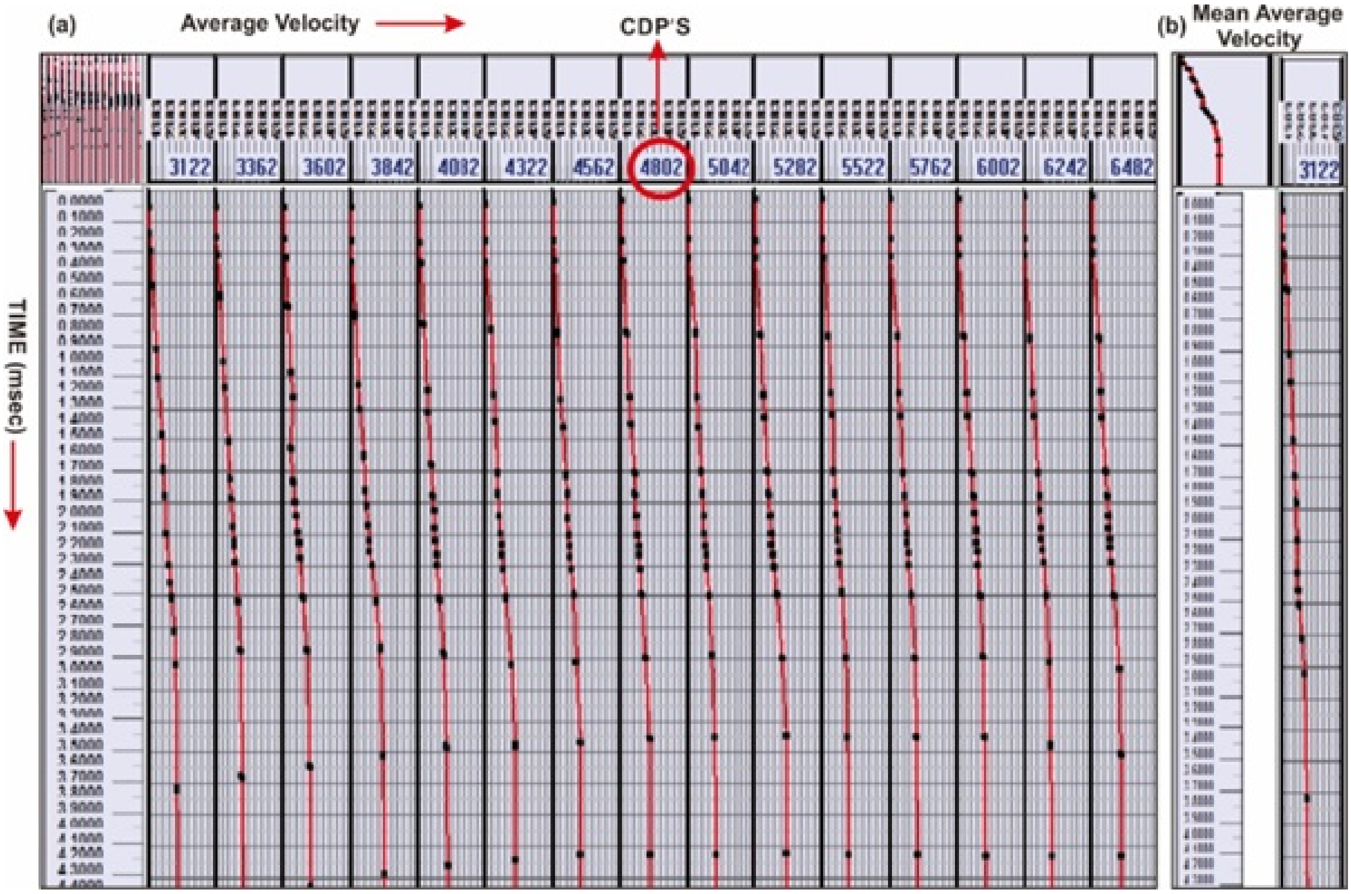

Figure 6 Average velocity (interpolated) of the line 9033-86. (b) Mean Average Velocity Graph of the line 9033-86

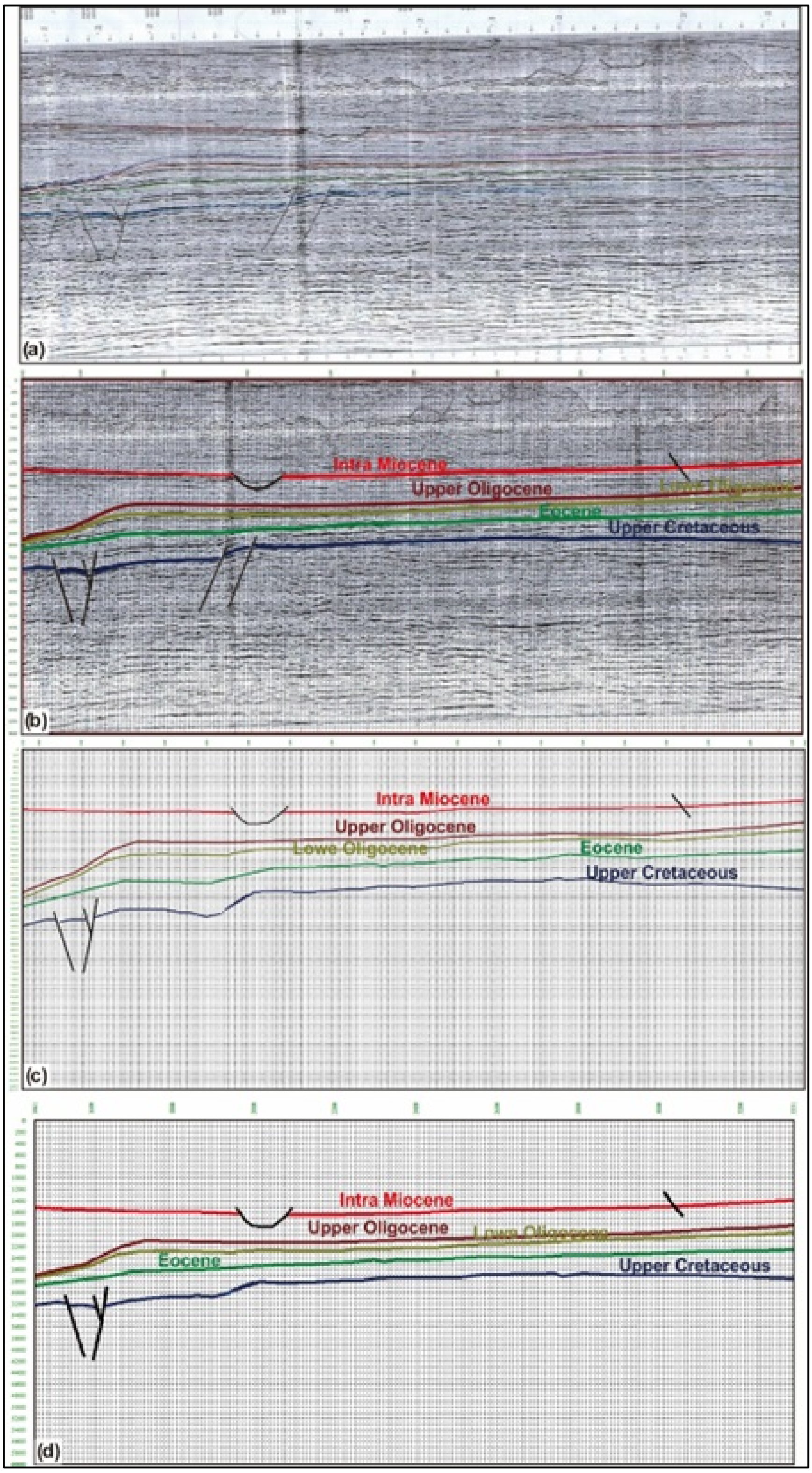

Figure 7 (a) Interpreted seismic line 9033-86. (b) Interpreted seism section of line 9033-86 with five reflectors that showing distortion in the NW. (c) Seismic Time section developed in K-tron. (d) Seismic Depth section developed in K-tron

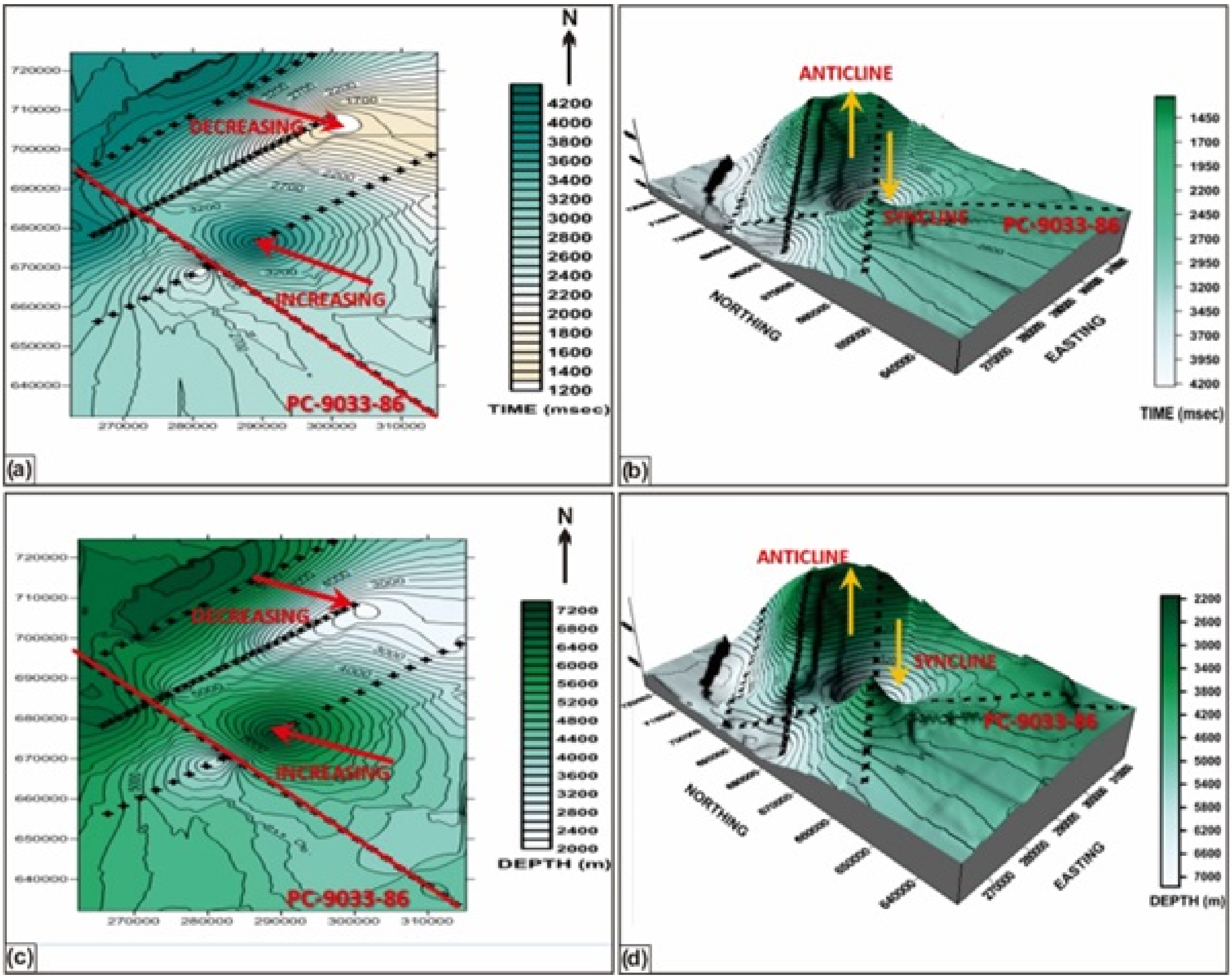

Figure 8 (a) Time Contour Map. (b) 3D Time-surface Contour Map. (c) Depth Contour map. (d) 3D Depth Surface Contour Map

CONCLUSIONS

The 2D seismic study of Indus Offshore Area, Pakistan shows the five horizons from upper cretaceous to intra Miocene are marked on the basis of general stratigraphy of the area. The seismic interpretation clarifies the several normal faults (horst and graben) and canyon faults. These normal faults will open new horizons for hydrocarbon exploration in the Indus offshore basin in Pakistan. Seismic time and depth interpretation indicate vertical and lateral velocity variations through various geological layers, interval velocity and average velocity graphs. The vertical changes in velocity are due to the change in density and lithology of the strata, whereas the horizontal changes are due to structural disturbance. Additionally, time and depth contour maps of the top of the Eocene show the anticline and syncline, which reflect the extensional tectonic regime and associated structural style. The trend of these reflectors shows that these are more or less parallel to each other while dipping towards the northwest. Consequently, the trapping mechanism identified from our interpretation that reservoir rocks in Indus Offshore Basin have tremendous reserves of hydrocarbons and the tectonics modification of the basin has formed a variety of trap structures.

ACKNOWLEDGEMENTS

The current research is a part of MSc work, which was completed by Moazzam Ullah Baig in Quaid-e-Azam University, Islamabad, Pakistan. We gratefully acknowledge Director General, Petroleum Concessions (DGPC) and LMKR, Pakistan, for the provision of data for this research work. We are also thankful to Mr. Khalid Amin Khan for providing the software.

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